

# A MODEL FOR STAR FORMATION, GAS FLOWS AND CHEMICAL EVOLUTION IN GALAXIES AT HIGH REDSHIFTS

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## ABSTRACT

Motivated by the increasing use of the Kennicutt-Schmidt (K-S) star formation law to interpret observations of high redshift galaxies, the importance of gas accretion to galaxy formation, and the recent observations of chemical abundances in galaxies at  $z \sim 2-3$ , I use simple analytical models to assess the consistency of these processes of galaxy evolution with observations and with each other. I derive the time dependence of star formation implied by the K-S law, and show that the sustained high star formation rates observed in galaxies at  $z \sim 2-3$  require the accretion of additional gas. A model in which the gas accretion rate is approximately equal to the combined star formation and outflow rates broadly reproduces the observed trends of star formation rate with galaxy age. Using an analytical description of chemical evolution, I also show that this model, further constrained to have an outflow rate roughly equal to the star formation rate, reproduces the observed mass-metallicity relation at  $z \sim 2$ .

*Subject headings:* galaxies: abundances—galaxies: evolution—galaxies: high-redshift

## 1. INTRODUCTION

The motivations of this paper are several. First, the empirical Kennicutt-Schmidt (K-S) law (Schmidt 1963; Kennicutt 1998), which states that the surface density of star formation is proportional to the surface density of gas, is widely used to interpret and describe star formation in galaxies, though its origins are not fully understood and it is just beginning to be tested at high redshift (Baker et al. 2004; Coppin et al. 2007; Bouché et al. 2007). The K-S law is a valuable tool when gas masses are not directly measurable; it has been used to estimate the gas masses of both high redshift galaxies (Erb et al. 2006c) and local galaxies in the distant past (Calura et al. 2007). The consequences of the K-S law for the evolution of star formation at high redshift are therefore worth considering in more detail, as is the consistency of these consequences with observations.

Second, the fueling of star formation by gas accretion is an essential element of models of galaxy formation, but has largely been neglected by observers of galaxies at high redshifts, mostly because of the lack of evidence for inflow in the spectra of these galaxies. In contrast, the evidence for strong outflows in galaxies at  $z \sim 2-3$  is well-known, most notably in the form of offsets between the redshifts of nebular emission lines, rest-frame UV absorption lines, and Ly $\alpha$  emission (Pettini et al. 2001, Steidel et al. 2007, in prep). In spite of the lack of observations of inflow, however, its effects should be considered in the context of other observations, since a significant inflow rate would affect other, measurable properties.

Finally, in recent years metallicity measurements of increasingly large samples of galaxies at  $z > 1$  have become possible (e.g. Kobulnicky & Koo 2000; Pettini et al. 2001; Savaglio et al. 2004; Shapley et al. 2004; Maier et al. 2006), including the detection of a mass-metallicity relation at  $z > 2$  (Erb et al. 2006a). These measurements still suffer considerably from lim-

itations on the methods that can be used and from calibration uncertainties, but nevertheless they offer a unique opportunity to place constraints on star formation histories and gas flows at high redshift, provided that the effects of inflow, outflow and star formation can be disentangled. Many recent studies have addressed this issue in some detail, including Köppen & Edmunds (1999); Köppen & Hensler (2005); Dalcanton (2007); and Finlator & Davé (2007).

The goal of this paper is to formulate simple, analytical models including star formation according to the K-S law, gas inflows and outflows, and chemical evolution. We would like to assess whether or not these models are consistent with each other and with our current observational knowledge of high redshift galaxies, and to see if they might give a general picture of how gas flows, star formation and metal enrichment may proceed at high redshift. In §2 I derive the explicit time dependence of star formation implied by the K-S law and test its consistency with observations of galaxies at  $z \sim 2$ . In §3 I consider simple models of chemical evolution which incorporate both inflows and outflows of gas, and again test their consistency with observations of high redshift galaxies and with the results of the previous section. Some implications of the results are discussed in §4. I adopt a cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ , and  $\Omega_\Lambda = 0.7$ , and use the Chabrier (2003) initial mass function (IMF).

## 2. THE TIME EVOLUTION OF STAR FORMATION ACCORDING TO THE KENNICUTT-SCHMIDT LAW

The first question is whether or not the locally observed K-S law is consistent with the observed and inferred masses, star formation rates (SFRs), and star formation histories of high redshift galaxies. This is most easily addressed by deriving the explicit time dependence of the K-S law, which is written as  $\Sigma_\phi = C\Sigma_{\text{gas}}^n$ , where the star formation rate is  $\phi(t)$ ,  $\Sigma_\phi = \phi(t)/r^2$  is the surface density of star formation, and  $\Sigma_{\text{gas}} = M_{\text{gas}}/r^2$  is

the cold gas mass surface density. I set  $n = 1.4$  according to Kennicutt (1998), and use  $C = 5.5 \times 10^{-13}$ . For  $n = 1.4$ , the Kennicutt (1998) value of  $2.5 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$  becomes  $1.0 \times 10^{-12}$  when the gas surface density is given in  $\text{M}_\odot \text{ kpc}^{-2}$  rather than  $\text{M}_\odot \text{ pc}^{-2}$ , and an additional factor of 1.8 accounts for the change from Salpeter to Chabrier IMF. When the K-S law is written as  $\Sigma_\phi = C \Sigma_{\text{gas}}^n$  and mass is given in  $\text{M}_\odot$ , time in years, and size in kpc,  $C$  has units of  $\text{M}_\odot^{1-n} \text{ yr}^{-1} \text{ kpc}^{2(n-1)}$ . For simplicity I assume that the galaxy size  $r$  remains constant with time; this is undoubtedly an oversimplification, but varying  $r$  between reasonable values makes no qualitative difference to the result. Neglecting (for the moment) inflows, outflows, and the gas returned to the ISM by star formation<sup>1</sup>, the gas mass is

$$M_g(t) = M_i - \int_0^t \phi(t') dt', \quad (1)$$

where the initial gas mass is  $M_i$ . Then the K-S law can be recast in terms of the SFR, the initial gas mass, and the size as

$$\phi(t) = C \left[ M_i - \int_0^t \phi(t') dt' \right]^n r^{2(1-n)}. \quad (2)$$

In order to solve for  $\phi(t)$ , we rearrange and isolate the integral:

$$\int_0^t dt' \phi(t') = - \left[ \frac{\phi(t)}{C r^{2(1-n)}} \right]^{1/n} + M_i. \quad (3)$$

Differentiating both sides and rearranging further leads to the differential equation

$$\frac{d\phi(t)}{dt} = A \phi(t)^{2-1/n}, \quad (4)$$

where  $A = -n(C r^{2(1-n)})^{1/n}$ . This has the solution

$$\phi(t) = n^{n/(n-1)} \left[ A t (1-n) + n \phi_0^{(1-n)/n} \right]^{n/(1-n)}, \quad (5)$$

where the initial star formation rate  $\phi(0) = \phi_0 = C M_i^n r^{2(1-n)}$ .

The behavior of this solution is shown in Figure 1, for an initial gas mass  $M_i = 10^{11} \text{ M}_\odot$  and a fixed size  $r = 5 \text{ kpc}$ . At early times the star formation rate is approximately equal to the initial SFR, while at late times it falls as a power law with  $\phi(t) \propto t^{n/(1-n)}$ . The early and late solutions meet at a break time

$$t_b = \frac{n \phi_0^{(1-n)/n}}{A(1-n)}. \quad (6)$$

Regardless of the initial gas mass and size, the star formation rate at the break time is 9% of its initial value, and about 80% of the final stellar mass has been formed;

<sup>1</sup> With the inclusion of the gas returned to the ISM by evolved stars, the gas mass at a given time is described by  $M_g = M_i - \alpha M_*$ , where  $M_*$  is the stellar mass and  $\alpha$  is the fraction of the total mass formed into stars that remains locked in long-lived stars and remnants. The lockup fraction  $\alpha$  is a decreasing function of time, as lower mass stars evolve off the main sequence, and also depends on the assumed IMF and on the mass of the remnants. I assume  $\alpha = 1$  for simplicity, but see further discussion at the end of this section and in §3. The issue is also reviewed by Tinsley (1980) and Gibson (1997), among others.

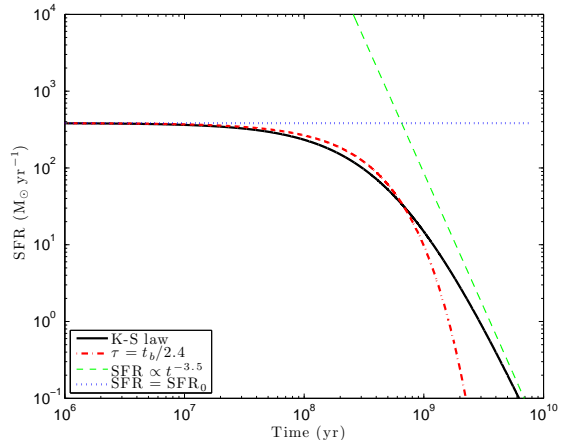


FIG. 1.— The solid black line shows the time evolution of the star formation rate given by the K-S law, for an initial gas mass  $M_i = 10^{11} \text{ M}_\odot$  and a fixed galaxy size  $r = 5 \text{ kpc}$ . At early times the SFR is approximately its initial value (blue dotted line), while at late times it falls as  $\phi(t) \propto t^{n/(1-n)}$  (green dashed line). The blue and green lines meet at the break time  $t_b$ . A comparable exponentially declining SFR is shown by the red dot-dashed line; in this case  $\tau = 270 \text{ Myr}$ .

TABLE 1  
STAR FORMATION RATES AND TIMESCALES

$M_i^a$ ( $\text{M}_\odot$ )	$\phi_0^b$ ( $\text{M}_\odot \text{ yr}^{-1}$ )	$t_b (f=0)^c$ ( $10^9 \text{ yr}$ )	$t_b (f=0.9)^d$ ( $10^9 \text{ yr}$ )
$10^9$	0.6	4.1	41
$10^{10}$	15	1.6	16
$10^{11}$	380	0.65	6.5
$10^{12}$	9600	0.26	2.6

<sup>a</sup> Initial gas mass <sup>b</sup> Initial star formation rate, assuming  $r = 5 \text{ kpc}$  <sup>c</sup> Break time with no inflow or outflow, assuming  $r = 5 \text{ kpc}$  <sup>d</sup> Break time with inflow rate 95% of gas processing rate, assuming  $r = 5 \text{ kpc}$

thus  $t_b$  represents a reasonable parameterization of the lifetime of the galaxy. For the parameters shown in Figure 1,  $t_b = 650 \text{ Myr}$  and  $\phi_0 = 380 \text{ M}_\odot \text{ yr}^{-1}$ ; for reference, values of  $t_b$  and  $\phi_0$  for other initial gas masses are given in Table 1. Also note that galaxies with larger masses have shorter star formation timescales, in accordance with observations that more massive galaxies form their stars at earlier times (e.g. Juneau et al. 2005; Panter et al. 2007).

The star formation history given by Equation 5 can be compared to the more familiar exponential star formation history  $\phi(t) \propto e^{-t/\tau}$  by setting the SFRs of the two models equal at  $t_b$  and determining the resulting value of  $\tau$ . The result is  $\tau = t_b/2.4$  (270 Myr for the example of Figure 1), and this exponentially declining SFR is shown by the red dashed line in Figure 1. The two star formation histories are quite similar until  $t_b$ , when the  $\tau$  model begins to decline more rapidly.

The time evolution of the SFR implied by the K-S law is compared with observations of  $z \sim 2$  galaxies in Figure 2. The left panel shows the above model for a range of initial gas masses, from  $M_i = 10^9 \text{ M}_\odot$  for the bottom blue curve to  $M_i = 10^{12} \text{ M}_\odot$  for the red curve at top. The galaxy size is again fixed at  $r = 5 \text{ kpc}$ , which is within a factor of  $\sim 2$  of measured galaxy sizes at these redshifts; varying  $r$  by a factor of two has no significant impact on the results. The black points

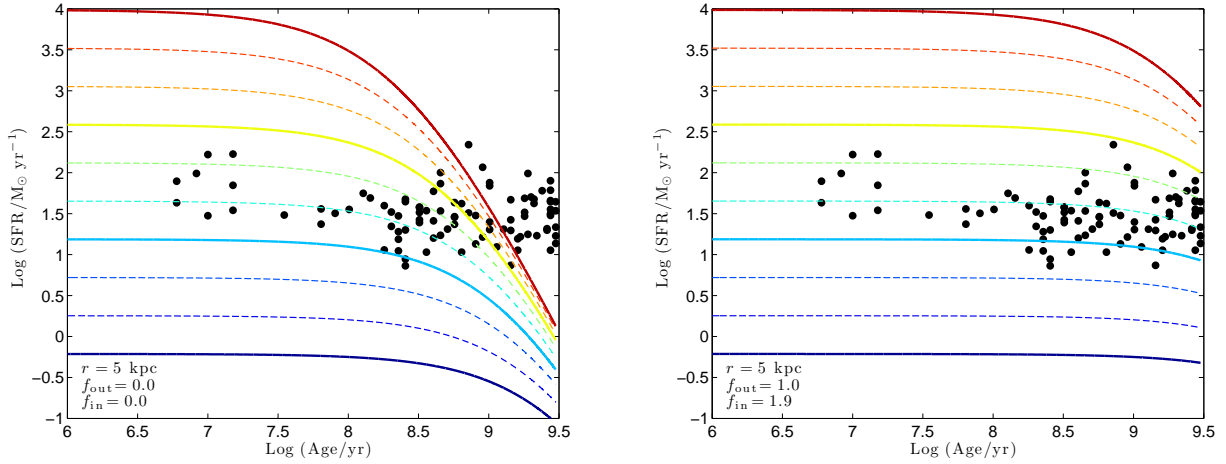


FIG. 2.— The time evolution of the star formation rate as predicted by the K-S law for a variety of initial gas masses  $M_i$ . From top to bottom, the solid lines show  $M_i = 10^9 M_\odot$  (dark blue),  $M_i = 10^{10} M_\odot$  (light blue),  $M_i = 10^{11} M_\odot$  (yellow), and  $M_i = 10^{12} M_\odot$  (red). The dashed lines show intermediate values. Data points are from Erb et al. (2006b). The left panel shows a closed box model with no inflows or outflows; the right panel shows an outflow rate equal to the star formation rate and a gas accretion rate 1.9 times the SFR, such that the accretion rate is 95% of the gas processing rate.

show data from Erb et al. (2006b), with star formation rates determined from extinction-corrected  $H\alpha$  emission and ages from spectral energy distribution (SED) modeling. Typical uncertainties are a factor of  $\sim 2$  in SFR and a factor of  $\sim 3$  in age, including uncertainties in the star formation history; the plotted points assume a constant star formation history. These data points are representative of typical star-forming galaxies at  $z \sim 2$ ; galaxies with significantly lower SFRs may exist but are too faint to be identified with current instrumentation, while galaxies with higher SFRs are relatively rare but can be identified by their strong IR or submillimeter emission (Papovich et al. 2006; Reddy et al. 2006; Chapman et al. 2005). As is usual with the comparison of smooth model star formation histories and real galaxies, the models can be assumed to represent either a broad time average of more episodic star formation events or a smooth, continuous process. The curves adequately represent many of the galaxies in the sample, but clearly do not account for the oldest galaxies, which still show significant star formation.

Star formation histories of high redshift galaxies are difficult to constrain, but there is considerable evidence for sustained (either continuous or episodic) star formation in galaxies at  $z \sim 2$ , and in galaxies with ages  $\gtrsim 1$  Gyr in particular. Old, massive (stellar mass  $M_\star \gtrsim 10^{11} M_\odot$ ) galaxies generally have the best understood stellar populations; Shapley et al. (2005) used SED modeling to show that massive, UV-selected galaxies are best fit with slowly declining star formation histories with  $\tau \sim 1$ –2 Gyr and ages of 2–3 Gyr (or by a burst of current star formation superposed on a maximally old stellar population). Papovich et al. (2006) observed massive, red ( $J - K > 2.3$ ) galaxies, most of which are still forming stars at a high rate at  $z \sim 2$ , and found that the earliest star formation was in the distant past and that most of the stellar mass had been accumulated well before the time of observation. Erb et al. (2006b) found from comparisons of  $H\alpha$  SFRs and inferred ages that the current SFR is a reasonable representation of the past average for most UV-selected galaxies at  $z \sim 2$ , but the most massive galaxies require higher past star formation rates.

Taking a different approach to star formation histories, Adelberger et al. (2005) used clustering observations to compare the number densities of UV-selected galaxies at  $z \sim 2$  and the haloes that can host them, and concluded from the roughly equal densities that the duty cycle (the fraction of time in which star formation is “on” at a level detectable by the UV selection criteria) of star formation in these galaxies is of order unity.

If star formation proceeds according to the K-S law as described above, no reasonable combination of size and initial gas mass can sustain star formation over the Gyr timescales required by these observations. Moreover, the galaxies have thus far been treated as closed boxes, which is certainly not the case; strong outflows are observed to be ubiquitous in star-forming galaxies at these redshifts (e.g. Pettini et al. 2001; Shapley et al. 2003; Smail et al. 2003), and observations at low and high redshifts suggest that the mass outflow rates are comparable to the star formation rate (Martin 1999; Pettini et al. 2000; Martin 2003). This clearly exacerbates the gas depletion problem; an outflow rate equal to the star formation rate effectively halves the lifetime of the galaxy.

The obvious solution is the accretion of additional gas, either in a continuous flow or through minor mergers. Such accretion is theoretically expected at these redshifts (see §4), although evidence for it in observed galaxy spectra is so far minimal. In order to sustain star formation over such protracted timescales, gas must be replenished at roughly the rate at which it is processed. This can be addressed analytically by adding a factor  $f$  representing the net gas flow rate to Equation 1:

$$M_g(t) = M_i - (1 - f) \int_0^t \phi(t') dt'. \quad (7)$$

The gas flow rate  $f = f_i - f_o$ , where the outflow rate  $f_o$  and the inflow rate  $f_i$  are given as fractions of the star formation rate. For  $f > 0$ , there is a net flow of gas into the galaxy, but for  $f < 1$  the total gas mass of the system decreases with time, because of the additional consumption of gas by star formation. As above, we find

$$\phi(t) = n^{n/(n-1)} \left[ A' t(1 - n) + n\phi_0^{(1-n)/n} \right]^{n/(1-n)}, \quad (8)$$

with  $A' = -n(1-f)(Cr^{2(1-n)})^{1/n}$  and the initial star formation rate  $\phi(0) = \phi_0 = CM_1^n r^{2(1-n)}$ . Note that the only difference between this solution and that of Equation 1 is the factor of  $(1-f)$  in the  $A'$  term.

This solution is shown in the right panel of Figure 2, which shows models with the same range of initial gas masses, but this time incorporating an accretion rate equal to 95% of the combined outflow rate and SFR. This particular solution has  $f_i = 1.9$  and  $f_o = 1$ , but any combination of inflow and outflow rates with  $f = f_i - f_o \simeq 0.9$  will show the same behavior. The result is a very shallowly declining SFR, well matched to the observations.

The models do not fit as well with even a small decrease in the accretion rate. An accretion rate of 85% of the gas processing rate requires most of the oldest galaxies to have  $M_i > 10^{11} M_\odot$ , and a further decrease to 80% fails to account for the SFRs of about half of the oldest galaxies with the range of initial gas masses considered. However, a modest reduction in the required accretion rate results from the inclusion of the gas returned to the ISM by evolved stars; as noted above, I have neglected this time-dependent effect in order to make the modeling more tractable, but an estimate of the mass of gas returned by star formation can be found from population synthesis models such as those of Bruzual & Charlot (2003). Assuming a Chabrier (2003) IMF, at an age of  $\sim 1$  Gyr a galaxy with a constant star formation rate of  $30 M_\odot \text{ yr}^{-1}$  (the average of the  $z \sim 2$  UV-selected sample) has returned a gas mass of  $\sim 10^{10} M_\odot$  to the ISM, for an average (but not constant) rate of  $\sim 10 M_\odot \text{ yr}^{-1}$ , or  $\sim 1/3$  of the SFR. If the outflow rate is roughly equal to the star formation rate, the required accretion rate is then  $\sim 5/6$  of the gas processing rate.<sup>2</sup> Finally, note that the essential ingredient here is a reservoir of new gas for star formation; this could be supplied by gas cooling and falling in from the halo as well as by gas newly accreted from the surrounding intergalactic medium (IGM).

Thus far we have constrained only the relative values of the inflow and outflow rates. Any model in which the accretion rate is approximately equal to the gas processing rate will satisfy the requirements imposed by the star formation rates and ages; for additional constraints on the magnitude of the inflows and outflows we must turn to measurements of the gas phase metallicity.

### 3. INFLOWS, OUTFLOWS AND THE MASS-METALLICITY RELATION

Erb et al. (2006a) observed a correlation between stellar mass and gas phase metallicity in star-forming galaxies at  $z \sim 2$ , and used the K-S law to infer the gas masses and gas fractions of the galaxies. By fitting simple chemical evolution models to the relationship between gas fraction and metallicity, they showed that closed boxes and models with low outflow rates were inadequate to reproduce the data; with outflows only, a high outflow rate of  $\dot{M} \sim 4 \times \text{SFR}$  was required. Given the above results, however, it's clear that such a model would deplete the galaxies' gas extremely quickly, and that the effect of gas inflows on metallicity must also be considered.

<sup>2</sup> If the Salpeter (1955) IMF is assumed, the average SFR of the UV-selected sample is  $\sim 50 M_\odot \text{ yr}^{-1}$ , but the rate of formation of massive stars that have returned material to the ISM is the same, since the IMFs differ only at the low end. Thus the result is similar for a Salpeter IMF.

I assume for simplicity that gas is accreted at a constant fraction  $f_i$  of the star formation rate; this can be viewed either as a continuous process or as the average of many minor events (for a thorough treatment of chemical evolution due to discrete events of accretion and star formation, see Dalcanton 2007). The outflow rate is also considered to be a constant fraction  $f_o$  of the SFR. Then the gas mass is given by

$$M_g = M_i - \alpha M_\star + f_i M_\star - f_o M_\star, \quad (9)$$

where  $\alpha$  is the fraction of mass remaining locked in stars. The metal content  $Z$  (defined as the fraction by mass of elements heavier than helium) evolves according to the standard differential equation

$$\frac{d(ZM_g)}{dM_\star} = y\alpha(1-Z) - \alpha Z - f_o Z, \quad (10)$$

where  $y$  is the true yield, the ratio of the mass of metals produced and ejected by star formation to the mass locked in long-lived stars and remnants. For a thorough discussion of the derivation of this equation, see Pagel (1997); the reviews by Gibson (1997) and Matteucci (2002) are also useful. I have assumed that the metallicity of the inflowing gas is negligible compared to that of the gas in the galaxy, and that the outflowing gas has the same metallicity as the gas that remains in the galaxy. I also assume for simplicity that  $\alpha = 1$ , i.e. the gas returned to the ISM by star formation is neglected. This is not always a good assumption; by an age of a few Gyr, the returned fraction approaches 40% of the total mass turned into stars for a Chabrier IMF.<sup>3</sup> However, most high redshift galaxies are younger than this, making the effect less significant, and a proper treatment of the time-varying  $\alpha$  is nontrivial.

For  $Z \ll 1$ , a condition which is always true, Equation 10 has the solution (e.g. Edmunds & Pagel 1984)

$$Z = \frac{y\alpha}{f_i} \left[ 1 - \left( \frac{M_g}{M_i} \right)^{\frac{f_i}{\alpha - f_i + f_o}} \right], \quad (11)$$

where the ratio of the current to the initial gas mass  $M_g/M_i$  can be written in terms of the gas fraction

$$\mu = M_g / (M_g + \alpha M_\star) \quad (12)$$

as

$$\frac{M_g}{M_i} = \frac{\mu}{1 + (1 - \mu)(f_o/\alpha - f_i/\alpha)}. \quad (13)$$

This result is shown in Figure 3, with the inflow rate fixed at 95% of the gas processing rate and a yield  $y = 0.019 = 1.5Z_\odot$ .<sup>4</sup> The solid red line shows the best fit model, with  $f_i = 2.2$  and  $f_o = 1.3$ , while the green dotted and dot-dashed lines bracket the range of reasonable fits, with  $f_i = 1.9$  and  $f_o = 1$  (the same parameters used in the right panel of Figure 2 above) at top and  $f_i = 2.5$  and  $f_o = 1.6$  on the bottom. It is likely that variations in gas flow rates produce scatter in the mass-metallicity relation (Finlator & Davé 2007), and the green lines may therefore give some indication of this variation.

<sup>3</sup> The returned fraction at this age is  $\sim 25\%$  for a Salpeter IMF, with its higher fraction of low mass stars.

<sup>4</sup> Using the solar metallicity  $Z_\odot = 0.0126$  (Asplund et al. 2004). Note that the ratio  $y/f_i$  provides the scaling of the models shown in Figure 3, so a lower yield would also lower the best-fitting accretion rate.

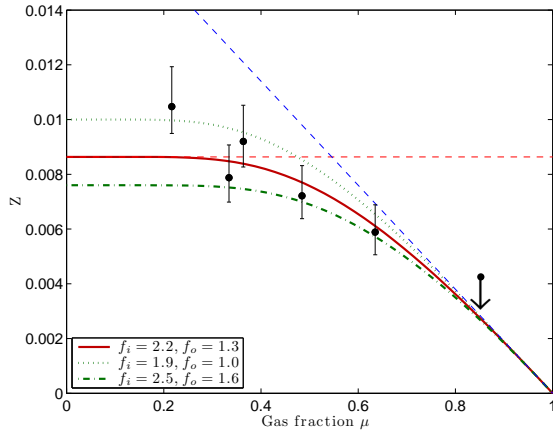


FIG. 3.— The evolution of metallicity with gas fraction as described by Equation 11. The data points indicate the metallicities and gas fractions found for  $z \sim 2$  galaxies by Erb et al. (2006a). Each point represents the average of 14 or 15 galaxies. The solid red line is the best fit to the data, and the green dotted and dot-dashed lines bracket the range of reasonable fits as described in the text. At high gas fractions  $Z$  rises with decreasing gas fraction as  $Z = y\alpha(1 - \mu)$  (blue dashed line), while at low gas fractions  $Z$  approaches the final metallicity  $Z_f = y\alpha/f_i$  (red dashed line).

### 3.1. Enriched Inflows and Enhanced Outflows

Thus far I have assumed that the inflowing gas is unenriched, and that the outflowing gas has the same metallicity as the gas remaining in the galaxy. Neither of these conditions are necessarily true; some of the inflowing gas may be gas expelled by winds falling back onto the galaxy, and metal-enhanced galactic winds have been observed locally (Martin et al. 2002). It is reasonably straightforward to incorporate these additional parameters into the chemical evolution model described above. If the metallicity of the inflowing gas is a fraction  $z_i$  of the metallicity of the gas in the galaxy, and the metallicity of the outflowing gas is a fraction  $z_o$  of the metallicity of the gas in the galaxy, then Equation 10 becomes

$$\frac{d(ZM_g)}{dM_*} = y\alpha(1 - Z) - \alpha Z - f_o z_o Z + f_i z_i Z. \quad (14)$$

Combining this with Equation 9 and solving, we find that at low gas fractions the galaxy reaches a final metallicity

$$Z_f = \frac{y\alpha}{f_i(1 - z_i) - f_o(1 - z_o)}, \quad (15)$$

and the evolution of metallicity with gas fraction is described by

$$Z = Z_f \left[ 1 - \left( \frac{M_g}{M_i} \right)^{\frac{f_i(1-z_i) - f_o(1-z_o)}{\alpha - f_i + f_o}} \right], \quad (16)$$

where  $M_g/M_i$  is related to the gas fraction by Equation 13 above. The final metallicity  $Z_f$  is shown by the dashed red line in Figure 3, for the simple case  $z_i = 0$  and  $z_o = 1$ . It is clear from Equation 15 that increasing the metallicity of the inflowing gas will also require an increase in the inflow rate in order to arrive at the observed  $Z_f \simeq 0.01$ , while further increasing the metallicity of the outflows will decrease the inflow and outflow rates required to reach this same  $Z_f$  (assuming that the inflow and outflow rates are related as required by the results of §2 above). The two effects may also cancel each other out; if, for example,  $z_i = 0.5$  and  $z_f = 1.5$ ,  $Z_f \simeq 0.01$

is reached with  $f_i = 2.2$  and  $f_o = 1.3$ , the same best-fit parameters shown in Figure 3 (although the shape of this model is slightly different). In this case the true accretion rate of new gas is only half that of the  $z_i = 0$  case, because half of the accreting gas is actually outflow gas returning to the galaxy.

The addition of two more free parameters clearly decreases our ability to constrain the gas flow rates; even with the inflow rate fixed at approximately the gas processing rate, the model now has many acceptable solutions. However, given the current lack of constraints on  $z_i$  and  $z_o$ , it seems sensible to adopt the simple model shown in Figure 3 for the purposes of further discussion. The range of parameter space shown provides an excellent match to the relationship between metallicity and gas fraction inferred for the  $z \sim 2$  galaxies, while satisfying the demands of the K-S law and all available information on gas flow rates.

## 4. DISCUSSION

The above results provide a coherent picture in which strong star formation is sustained by the accretion of gas at approximately the gas processing rate, the outflow rate is roughly equal to the SFR, and metal enrichment is modulated by both outflows and inflows. This is not a new result; Finlator & Davé (2007) reached many of the same conclusions using cosmological hydrodynamic simulations to reproduce the  $z \sim 2$  mass-metallicity relation, and the idea of a system in which star formation is balanced by inflow dates to work by Larson (1972) and Tinsley & Larson (1978). Whatever the methods used to reach these conclusions, however, many questions remain about the mechanisms of gas flows and chemical enrichment at high redshift.

The only quantity not yet tied to observations is the gas accretion rate, which the models require to be approximately equal to the gas processing rate. If the outflow rate is roughly equal to the SFR, the required accretion rate is  $\sim 60 M_\odot \text{ yr}^{-1}$  (assuming the average SFR of the UV-selected sample; Erb et al. 2006b), and as much as several hundred  $M_\odot \text{ yr}^{-1}$  or higher for the most rapidly star forming galaxies. These values are in general agreement with theoretical expectations. For example, the predicted average gas accretion rates for galaxies in  $10^{12} M_\odot$  haloes<sup>5</sup> given by Kereš et al. (2005) are  $\sim 50 M_\odot \text{ yr}^{-1}$  at the relevant redshifts, rising to several hundred  $M_\odot \text{ yr}^{-1}$  for the  $10^{13} M_\odot$  haloes expected to host the most massive galaxies (though more recent simulations indicate rates a factor of  $\sim 2$  or more lower; D. Kereš, private communication). Gas accretion and cooling rates from the semi-analytic models of Croton et al. (2006) are also of the right order of magnitude.

The question remains as to why such high accretion rates have not yet been observed. One difficulty is that the velocity range of inflowing gas is likely to be much narrower than the several hundred  $\text{km s}^{-1}$  spread observed in the outflows. Another suggestion is that cold, filamentary accretion may dominate at high redshifts (Kereš et al. 2005; Dekel & Birnboim 2006), in which case detection would depend strongly on projection effects; alternatively, the accretion could occur largely in

<sup>5</sup> Clustering results indicate that the  $z \sim 2$  UV-selected galaxies are typically associated with  $\sim 10^{12} M_\odot$  haloes (Adelberger et al. 2005).



the form of minor mergers. Another possibility is that the accreting gas may be too hot to produce signatures in the observed wavebands, or such signatures may simply be too weak to detect. Even if the hot accreting gas does produce C IV emission, for example, the line would likely be weak because of the low metallicity of the gas, and it would be superposed on the already complicated C IV profile. Detailed modeling of the likely line strengths would help to place limits on detectable accretion rates. Gas heated to the virial temperature of  $\sim 10^6$  K must also be sufficiently cooled in order to fuel star formation; work by Yoshida et al. (2002) and Croton et al. (2006), among others, discusses the mechanisms by which this might proceed.

The strong star formation and gas accretion discussed herein will not continue indefinitely. Observations suggest that most of the star-forming galaxies currently detected at  $z \sim 2-3$  will become largely passively evolving by  $z \sim 1$  (Adelberger et al. 2005; Papovich et al. 2006). Because the high observed star formation rates require accretion of new gas to sustain, a decline in the SFR is a natural consequence of the drop in accretion rates at lower redshifts predicted by theoretical models. Many theorists and observers have also proposed that AGN feedback may be responsible for the termination of star formation (e.g. Hopkins et al. 2006 and references therein). If an additional mechanism to shut off star formation is required, this is a plausible candidate, as the ubiquity of outflows suggests that starburst-driven winds

may regulate star formation but do not usually terminate it, and this work implies that strong accretion and outflows may operate simultaneously, or at least alternate in relatively quick succession.

Finally, these results underscore the importance of metallicity measurements for understanding gas flows. Until the flows can be observed and quantified directly, measurements of gas phase abundances offer the best hope for constraining the outflow and inflow rates of galaxies at high redshift. There are still considerable difficulties associated with the measurements of these metallicities, but we look forward to improved constraints from new IR spectra and photoionization modeling, and to more direct estimates of outflow rates from detailed spectra (e.g. Pettini et al. 2000). Such measurements will give a far more robust picture of star formation, gas flows and metallicity at high redshift than these simple models can provide.

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